Control Rod Treatment in the HELIOS/MASTER Code Package for the Prismatic VHTR Physics Analysis

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1. Introduction

New nuclear design procedure based on the two-step procedure is under development for the reactor physics analysis of the very high temperature gas-cooled reactor (VHTR).[1] The HELIOS[2] code was employed for the transport lattice calculation to generate a few group constants, and the MASTER[3] code for the 3-D core calculation to perform the reactor physics analysis. All the analysis procedures have been developed except for the control rod treatment. That the reactivity of the VHTR core is controlled only by the control rod requires a good accuracy in the control rod treatment.

In this study we developed how to deal with the control rod movement through the mini core model and the optimization of the number of energy groups and boundaries. This procedure was verified through the benchmark calculations for the simplified NGNP[4] cores, where the reference solutions were obtained from the MCNP[5] calculations.

2. Methods and Results

2.1 A Mini Core and a Simplified Core Models

A mini core and a simplified NGNP core models were developed for an easier development of the analysis procedures as shown in Figures 1 and 2. Since the NGNP core includes 3 columns of blocks, a mini core model also includes 3 blocks to be equivalent in its optical length. Each block includes 14 pin cells where the fuel compact is the same as the real one and the pin cell pitch has been decided to preserve the graphite moderator volume per fuel compact. In a simplified core model, the NGNP core was modified to be 1/6 symmetric by moving the control rod hole to the center of the block. In the prismatic NGNP, there are two different types of control rods called a regulating (R) and a shutdown (S) control rod. A regulating control rod is located in the reflector to keep a reactor core critical during an operation, and a shutdown one in the fuel blocks to shut down the reactor core in emergency or for maintenance. Control rod worths were estimated for a combination of these control rods. In this study, a double heterogeneity of the fuel compact was eliminated by the RPT[6] (Reactivity-equivalent Physical Transformation) method.

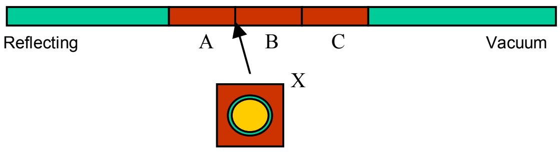

Figure 1. The VHTR mini core model

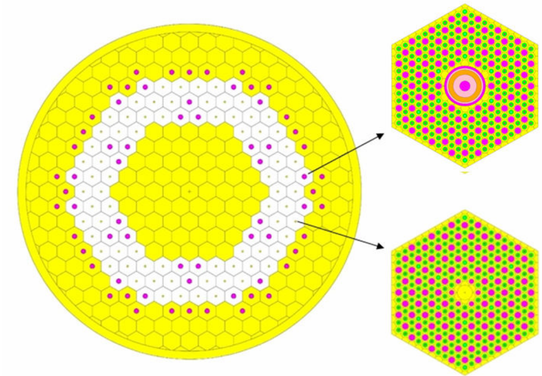

Figure 2. The simplified NGNP core

2.2 Energy Group Boundary

In order to handle the effects of the spectrum shift and upscattering appropriately, we performed a study to find an optimum neutron energy group structure to be used in the MASTER 3-D core calculation. By exploring the HELIOS calculations for the mini cores with different control rod configurations at various temperatures and burn-ups, we optimized the number of energy groups and their boundaries within which all the cross sections become so relatively environmental-free that they may be calculated by a simple spectral geometry. The number of energy groups and boundaries were optimized to make the reaction rate and reactivity changes of the fuel block minimum according to the control rod insertion. This process could be performed automatically by the GRBOUND program, and the resultant number of energy groups and boundaries are shown in Table 1.

Table 1. Energy group boundaries for NGNP

Group	Upper (eV)	Group	Upper (eV)
1	2.000000E+07	6	2.907404E-01
2	2.144498E+02	7	2.276891E-01
3	6.868019E+00	8	1.115699E-01
4	9.710043E-01	9	4.999990E-02
5	4.170395E-01	10	2.049193E-02

2.3 A Mini Core Calculation

The B_4C control rods were inserted with five different combinations: No(Case0), A(Case1), B(Case2), C(Case3), outer reflector(Case4), and A and outer reflector(Case5). The reference solutions were obtained from the HELIOS calculations with the 190 group library. Macroscopic cross sections for a block with and without a control rod insertion were edited from the HELIOS outputs according to the 2-step procedure. The FDM (Finite Difference Method) diffusion calculations were performed with various combinations of the block, reflector and control rod cross sections (Cases A~D). As shown in Table 2, the computational results showed that it is enough to include only an absorption cross section for the control rod in an additive term excluding the scattering cross sections, and all the reflector cross sections can be obtained from the mini core calculation without a control rod insertion.

Table 2. Comparison of the control rod worths in the mini core

Case	Rod position	HELIOS Keff.	FDM			
			A	B	C	D
0	No	1.36806	1.36797			
1	A	1.11181	1.10262	1.11701		
2	B	0.94781	0.93847	0.93038		
3	C	1.16623	1.15122	1.1501		
4	Refl.	1.2666	1.26538	1.26353	1.26289	1.26188
5	B, Refl.	0.9376	0.94963	0.91307	0.90722	0.90019
Case		Worth(pcm)	Error (%)			
1	A	-16847	-4.4			
2	B	-32410	-3.2	-6.1		
3	C	-12650	-8.8	-9.5		
4	Refl.	-5855	-1.2	-3.2	-3.9	-5
5	B, Refl.	-33559	4.0	-8.5	-10.6	-13.2

A : Block:Region XS / Reflector:Equivalent XS
B : Block:Region XS / Reflector:Equivalent XS from w/o Rod Case
C : Block:Region XS / Reflector:Equivalent XS from w/o Rod Case / Reflector Rod:Replace Σa only
D : Block:Region XS / Reflector:Equivalent XS from w/o Rod Case / Reflector Rod:Replace Σa & adjusted by dis-factor

2.3 Benchmark Calculation for the Simplified NGNP Core

We performed the benchmark calculations for the simplified NGNP cores with various control rod insertions. Table 3 provides a comparison of the control rod worths of HELIOS/MASTER with those of MCNP for the simplified NGNP cores. Macroscopic cross sections of Cases A and B are from a single block and a mini core models, respectively. Control rod worths of Case A and Case B are very consistent with those of MCNP. However, there is a power tilt in the HELIOS/MASTER power distributions when compared with those of MCNP. The outer block powers were underestimated and the inner block ones overestimated as shown by the mini core calculations. This phenomenon requires an improvement in treating the discontinuity factors between blocks when the R control rods are inserted.

Table 3. Comparison of the control rod worths for NGNP

Temp (K)	Rod	MCNP		HELIOS/MASTER					
		Keff	Worth (pcm)	Single (Case A)			Mini Core (Case B)		
				A	B	C	A	B	C
300	ARO	1.42671	-	207	-113	-113	-113	-	-
600		1.40045	-	232	-67	-67	-67	-	-
900		1.37714	-	131	-84	-84	-84	-	-
300	S-in	1.17286	15170	-676	-954	-954	-954	-5.8	-882
600		1.12894	17173	-577	-815	-815	-815	-4.7	-809
900		1.09292	18884	-767	-832	-832	-832	-4.8	-897
300	C-in	1.33493	4819	-161	-693	-693	-693	-7.6	-368
600		1.30166	5419	-21	-537	-537	-537	-4.7	-252
900		1.27305	5937	-29	-452	-452	-452	-2.7	-160
300	ARI	1.09515	21220	-990	-1543	-1543	-1543	-5.6	-1197
600		1.0492	23905	-828	-1341	-1341	-1341	-4.4	-1060
900		1.01175	26224	-937	-1262	-1262	-1262	-4.1	-1067

A : Reactivity difference in pcm
B : Rod worth difference in %
C : Rod worth difference in pcm

3. Conclusion

We developed a procedure to deal with a control rod movement. The control rod movement could be treated properly by optimizing the number of energy groups and boundaries, and adjusting the control rod cross sections with an equivalence theory[7]. Cross section of the block with a control rod insertion could be described as a difference of absorption cross section between the blocks with and without the control rods. It is required to improve the block power distribution in the case of a control insertion.

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